IN SITU PERMEABILITY MEASUREMENTS WITH DIRECT PUSH TECHNIQUES

TECHNOLOGY DESCRIPTION

The Cone Permeameter™ incorporates multiple pressure measurements along the axis of a cone penetrometer rod with a measured flow rate and a well-defined injection zone. The permeability value is obtained by applying a one-dimensional, spherical, steady-state Darcy flow model to the measured injection rate and pressure profile. The pressure field is distorted near the injection point by a combination of the cylindrical injection zone and the compacted soil near the rod surface. However, as the distance from the injection point is increased, the resulting pressure distribution will become spherical. As the radial distance from the source increases, the isobars intersect the cone rod in an almost perpendicular fashion, minimizing any azimuthal gradient that exists across the compacted annulus. By sensing the pressure gradient along the rod at a distance from the injection point, this method is able to essentially ignore the distortion of the pressure field near the injection zone.

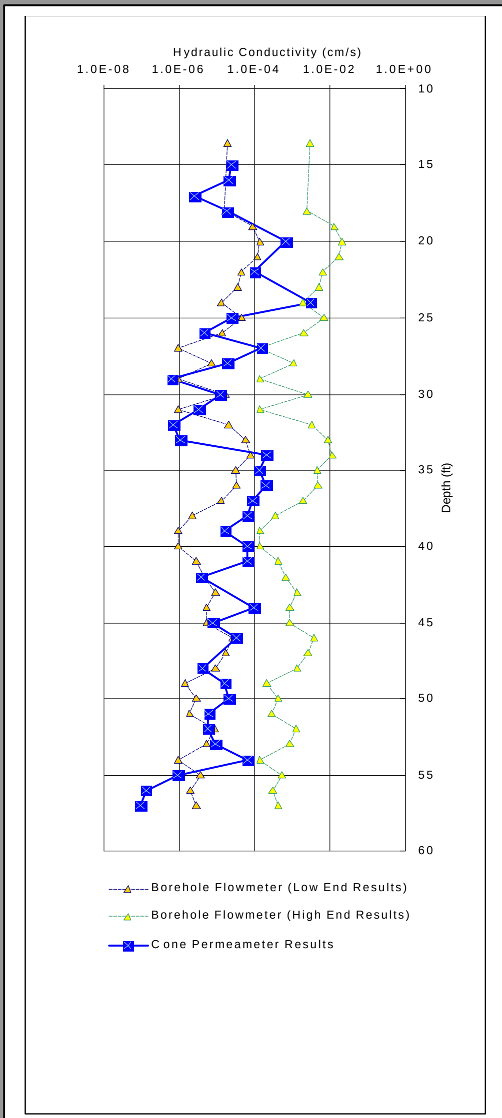
A penetrometer rod section is fabricated to allow air or water injection through a screened region. The radial pressure profile is measured with multiple pressure measurement ports distributed above or below the extraction zone. These points are filtered penetrations into the probe that allow pressure communication to sensors embedded in the rod. The Cone Permeameter™ is fabricated in a standard 2-inch diameter rod with five pressure ports ranging from 0.02 m to 0.8 m from the injection zone. At the surface, a fluid pumping system controls the injection flow rate. The data system collects the flow rate and resulting pressure profiles, allowing the calculation of the inferred permeability in real time.

The Cone Permeameter™ rod incorporates a proven fluid injection design and highly accurate pressure sensing elements embedded in the rod. The design allows the permeability meter measurements to be conducted simultaneously with standard Cone Penetrometer Test (CPT) cone measurements (pore pressure, tip and sleeve stress), which results in real-time, complementary data sets of soil type and hydrologic properties. The data system provides detailed analyses of pressure profiles and process histories for real-time display.

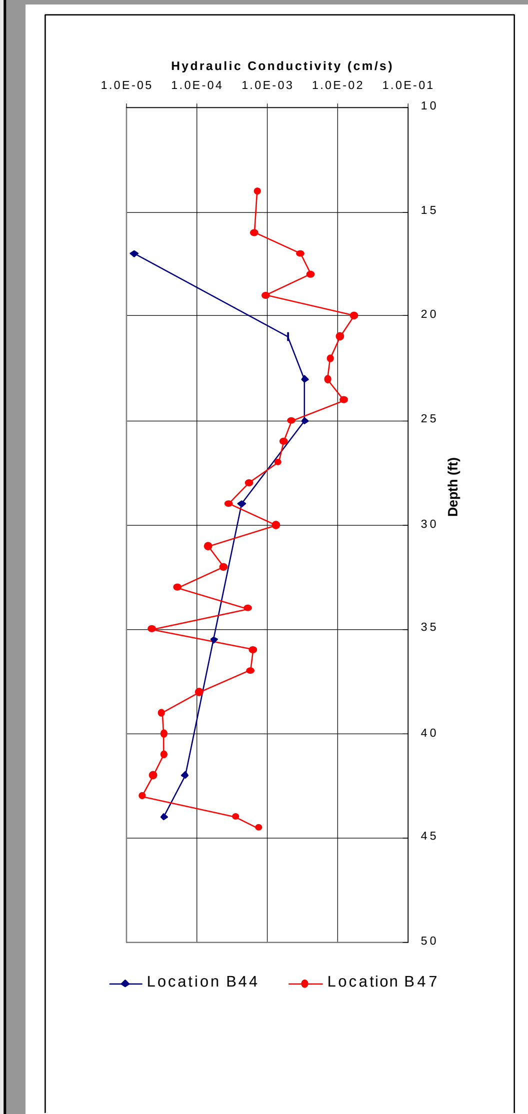
TECHNOLOGY NEED

In situ permeability measurements are required to predict contaminant transport and effectively design any soil remediation process relying upon fluid movement. Under a given pressure gradient, flow is directly proportional to permeability. Direct push borehole formation techniques provide fast and inexpensive borehole access for characterization, monitoring, and remediation purposes. However, because cuttings are not removed from the hole and the geologic media are instead displaced outward around the hole, direct push techniques significantly alter the fluid permeability of the soil immediately adjacent to the hole. This effect has precluded the use of standard techniques for measuring *in situ* gas and water permeability with cone penetrometers.

Baseline technologies used for obtaining soil permeability measurements include both borehole and cone penetrometer methods. The most common borehole technique is the measurement of total flow from the borehole under vapor extraction or pump test drawdown conditions. This method has the disadvantage that there is no vertical resolution of the permeability distribution. The second borehole method is to deploy straddle packers and then measure the flow rate and pressure drop from an isolated borehole section under extraction or injection conditions. This approach uses bulky equipment and ideally requires an open borehole. A major disadvantage of both methods is the high cost of drilling a borehole. Using a cone penetrometer, one can determine permeability in saturated media by measuring pore pressure with standard geophysical tools, given that the soil has low permeability. The “pore pressure dissipation" technique capitalizes upon the pressure that accumulates adjacent to the penetrometer during emplacement, and the dissipation of this pressure with time. This approach requires some understanding of soil properties and is limited to saturated soils of very low permeability.



Cone Permeameter™ Hydraulic Conductivity Profiles in the Coal Pile Runoff Basin at the Savannah River Site (SRS) Compared to Borehole Flowmeter Profiles



Hydraulic Conductivity Profiles of Locations B44 and B47 at Launch Complex 34, Cape Canaveral Air Station, Florida

There is a need for *in situ*, direct push characterization technologies to provide real-time analysis of volatile organic compounds (VOCs), metals, radionuclides, and hydraulic conductivity. Each year at the Savannah River Site (SRS), for example, approximately 10 Waste Unit sites are characterized, and approximately 200 to 400 samples are collected at each Waste Unit site.

The Site Technology Coordination Group (STCG) Need Number addressed is:

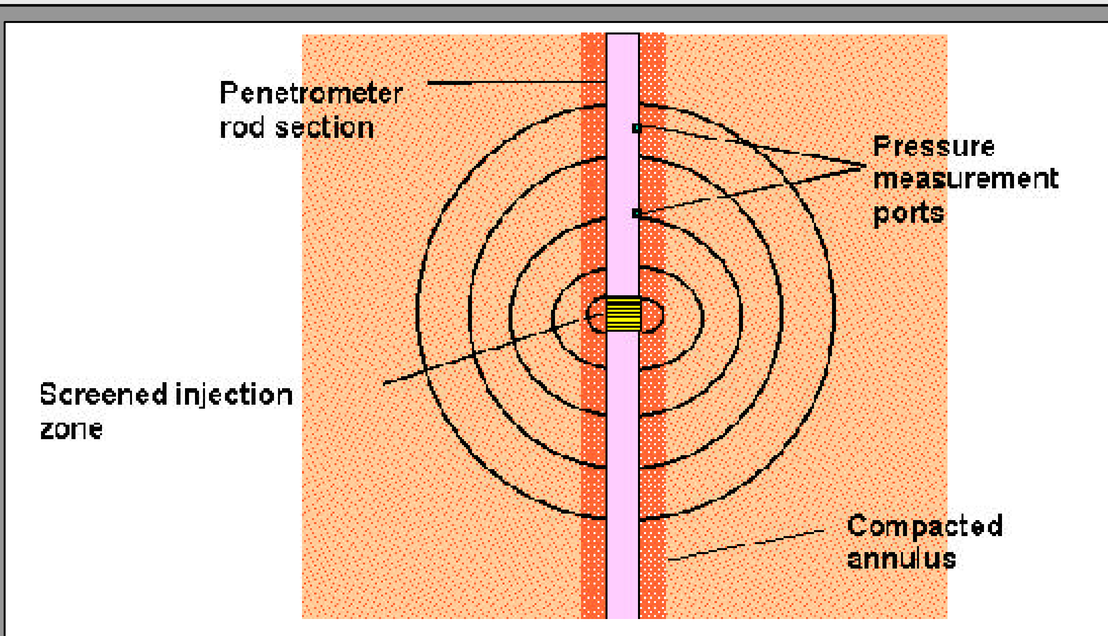
SR-3012 - *In Situ* (Direct Push) Characterization Technologies to Provide Real-Time Measurement of Hydraulic Conductivity and Analysis of Volatile Organic Compounds, Metals, and Radionuclides.

TECHNOLOGY BENEFITS

The benefits of the Cone Permeameter™ method include:

- Cost for measurements are less than half of borehole measurements.
- Measurement is rapid and integrated with other geophysical measurements.
- Small volumes of injected fluid due to small region of influence.
- Rapid measurements (3-10 minutes per station).
- Minimizes impact of compacted soil due to penetrometer emplacement.
- Integrated with CPT geophysical measurements.
- Makes use of all the benefits of cone penetrometer emplacements:
  --Minimal secondary waste.
  --Rapid mobilization and setup.
  --Low unit measurement cost.
  --Mature technology.

The initial field test of the Cone Permeameter™ system demonstrated its ability to conduct tests rapidly. In a period of 5 hours, 35 measurements were conducted in the saturated zone. These measurements were obtained concurrently with standard cone geophysical measurements, providing a highly integrated data set. Depending on the scenario, this approach will save at least 50 percent over conventional permeability measurement techniques, primarily because of the high cost of borehole formation with drilling techniques.



In the field, the Cone Permeameter™ acquires multiple pressure measurements along the axis of a penetrometer rod with a well-defined injection zone and a measured flow rate.

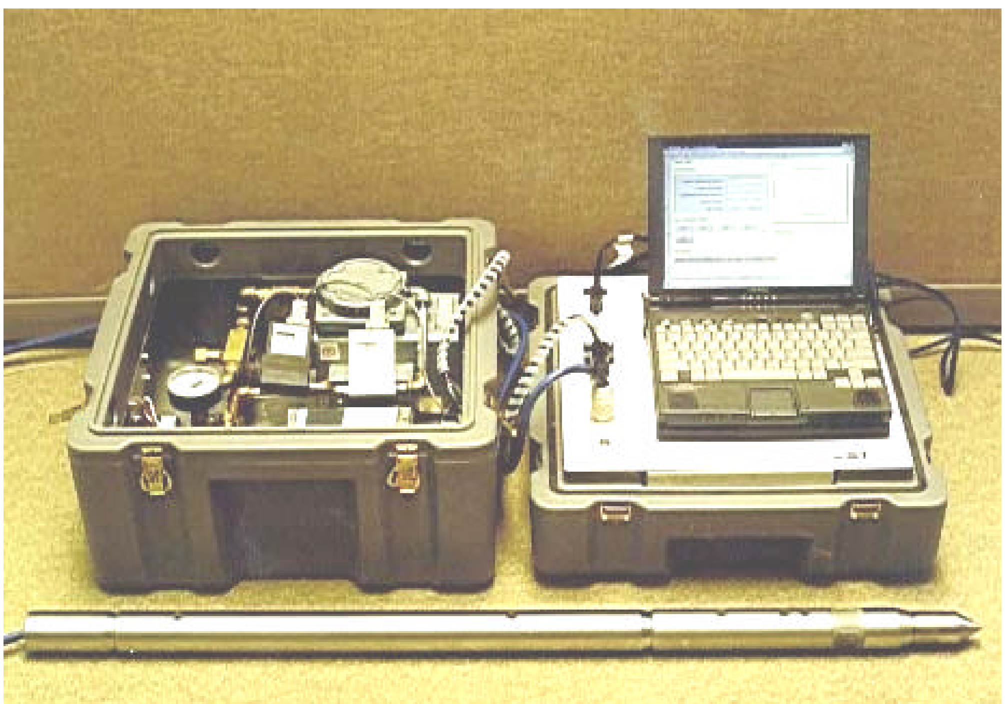
TECHNOLOGY CAPABILITIES/LIMITATIONS

The depth of deployment for the Cone Permeameter™ system is the same as the depths achievable with cone penetrometers. The depth is, therefore, highly site-dependent, but penetrometers typically can be deployed to depths of 100 feet or more in unconsolidated soils. The range of permeabilities that can be measured with the Cone Permeameter™ encompass the millidarcy to tens of darcies for air permeability, and 10^{-6} to 10^{-1} cm/s for saturated hydraulic conductivity measurements. Clays can pose difficulties for two reasons. The first is that the pore pressures accumulated due to the penetrometer emplacement in the saturated zone may require many minutes to dissipate. Very low permeability will impact the Cone Permeameter™ measurement, requiring long waits for steady-state conditions to be achieved. Under these conditions (less than 10^{-6} cm/s), the standard pore-pressure-dissipation technique may be the most appropriate. The second reason is that the pressure ports may become plugged with clay during air measurements. The ports can be plugged by clay under saturated conditions, but since it has a finite permeability to water flow the net effect is to only slow the pressure measurement response. For the air measurements, however, the clay may be very close to saturation and have effectively zero permeability to air flow–especially when very low pressure differentials are applied. These conditions can essentially plug the ports. The port design of the Cone Permeameter™ system is being changed to minimize the accumulation of clay over the porous filter material.

COLLABORATION/TECHNOLOGY TRANSFER

The Cone Permeameter™ technology has a patent pending. SEA Inc. expects to license the technology to a vendor of penetrometer measurement systems once the design is finalized. Applications for smaller direct push systems, such as Geoprobes™, are being investigated.

Collaboration with Applied Research Associates, Inc., (ARA) was key to the development of the prototype probe. ARA designed and fabricated the rod section and supported the demonstration tests at SRS with their CPT truck.



The Cone Permeameter™ is shown above in front of its portable data acquisition system. The data acquisition system measures the flow rate and the pressure profile, and from that input it calculates the inferred permeability in real time.

ACCOMPLISHMENTS AND ONGOING WORK

The initial research and feasibility assessment of this system were completed in early 1997 as the first phase of a contract supported by the DOE Characterization, Monitoring, and Sensor Technology Crosscutting Program (CMST-CP) through the DOE Federal Energy Technology Center (FETC). Numerical modeling and laboratory tests demonstrated that the basic premise of the system's operation was credible. The pressure fields resulting from the injection of air and water into a mockup probe were spherical, and they could be measured in such a fashion that near field compaction resulting from the penetrometer emplacement could be avoided. Results of this study are documented in the topical report titled "*In situ* Permeability Measurements with Direct Push Techniques: Phase I Topical Report" published by FETC (November, 1997, Science and Engineering Associates, Inc., Report Number SEA-SF-96-147.)

In the second phase of the development program, a prototype permeameter system was developed and proof-tested in a laboratory test cell. The system was then prepared for initial field trials. In April 1998, the Cone Permeameter™ measurement system was successfully deployed in both the saturated zone and vadose zone in three separate areas of the SRS. Results from this effort showed excellent agreement with previous permeability testing done at the site and had a positive correlation with concurrent cone penetrometer geophysical measurements (i.e., the permeability was higher in layers identified as sands and lower in areas composed of clay). At Coal Pile Runoff Basin 35 in the D Area at the SRS, 35 saturated measurements were conducted in a five-hour period (see the figure on the next page for the profile of this measurement sequence). Measurements in the vadose zone were problematic due to the existence of clay-rich soil at the SRS, which caused plugging of the injection zone and pressure ports. System development and demonstration are documented in the topical report "*In Situ* Permeability Measurements with the Cone Permeameter™ Measurement System Phase II Topical Report" (Lowry et al., 1998), which is currently under review by the DOE.

A second demonstration, sponsored by Westinghouse Savannah River Company, was conducted in June 1998 at the Old Radioactive Waste Burial Ground of SRS. In this technology fielding, the system was pushed to depths of 2 and 3 feet in order to measure the air permeability of the burial grounds landfill cover. Twenty-one measurements were completed with an average measurement time of 8 minutes. The results showed a wide range of permeabilities from 0.0002 to 1.2 darcies (2.3×10^{-16} to 1.2×10^{-12} m^2). The results appeared credible, considering that measurements were performed at a shallow depth where moisture contents can vary significantly in time and space.

In November 1998 the system was deployed at the 200 East Area of the Hanford Site to conduct *in situ* permeability measurements. This third demonstration was a joint venture with Applied Research Associates, Inc., and was funded by Lockheed Martin Hanford Company. Its objective was to evaluate the ability of the Cone Permeameter™ to measure air permeability at an arid site composed of sands, silts, and gravels. The air permeability measurements went much smoother in the Hanford environment. A total of 33 measurements were performed in four separate push locations with an average measurement time of 8 to 10 minutes. The maximum depth pushed over the demonstration period was 60 feet and the resulting permeabilities ranged from 0.03 to 8.2 darcies (3.28×10^{-14} to 8.16×10^{-12} m^2) Measured permeability profiles at adjacent pushes, distanced 1 foot apart, were within one order of magnitude. The system's equivalent hydraulic conductivity measurements and laboratory measurements of borehole core sample were in agreement within one-half order of magnitude.

In the third and final phase of this year's project, the Cone Permeameter™ was deployed at Launch Complex 34 of the Cape Canaveral Air Station in December 1998 and January 1999. Hydraulic conductivity measurements were performed at the request of the Interagency DNAPL Consortium (IDC) with the intention of aiding the preliminary site characterization of Launch Complex 34. Forty-four (44) measurements were completed in two separate locations. The total depth pushed during the operation was 44.5 feet and the resulting hydraulic conductivities ranged from 1.28×10^{-5} to 1.78×10^{-2} cm/s (equivalent to 0.013 to 18.5 darcies). Permeability profiles, distanced 10 feet apart, were within one order of magnitude (see the figure below). The results of this study are documented in the topical report titled

"*In Situ* Permeability Measurements with the Cone Permeameter™ Measurement System, Phase III Topical Report" (Lowry et al., 1999).

TECHNICAL TASK PLAN (TTP) INFORMATION

TTP No./Title: AC21-96MC33124 - *In Situ* Permeability Measurements with Direct Push Techniques

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